AD A108868

AFGL-TR-81-0201

LEVEL II

CRYOGENICALLY COOLED INFRARED INTERFEROMETRIC SPECTROMETERS

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30 June 1981

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SCIENTIFIC REPORT NO. 2

This research was sponsored by the Defense Nuclear Agency under Subtask S99QZXHI004, Work Unit 11, entitled: IR Phenomenology and Optical Code Development

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-81-0201	2. GOVT ACCESSION NO. AD-A108 868	3. RECIPIENT'S CATALOG NUMBER EDL-SRL-81-1
4. TITLE (and Subtitle) Cryogenically Cooled Infrared Interferometric Spectrometers		5. TYPE OF REPORT & PERIOD COVERED Scientific Report No. 2
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ronald J. Huppi and Allan J. Steed		8. CONTRACT OR GRANT NUMBER(s) F19628-78-C-0018
9. PERFORMING ORGANIZATION NAME AND ADDRESS Electro-Dynamics Laboratories (SRL) Utah State University 139 The Great Rd., Bedford, MA. 01730		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 767011AB
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory Hanscom AFB, Massachusetts 01731 Monitor: Capt. R.P. Walker/OPR		12. REPORT DATE 30 Jun 1981
		13. NUMBER OF PAGES 51
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; Distribution unlimited.

17. DISTRIBUTION ST ENT (of abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY TES

This research was sponsored by the Defense Nuclear Agency under Subtask S99QAXHI004, Work Unit 11, entitled: IR Phenomenology and Optical Code Development.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Interferometer, spectrometer, infrared, noise limitations, cryogenic cooling.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Very sensitive Fourier transform spectrometers (FTS's) have been developed for infrared measurements utilizing advanced technology to achieve stable operation at very low temperatures. All of the structural, optical, and detector components used to construct these spectrometers are cryogenically cooled to improve the sensitivity of their detectors and to eliminate unwanted background emission signals from the components. Various designs

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of cooled FTS systems which have been successfully used and tested by USU and AFGL are presented in the paper. The performance specifications, the advantages, and the limitations of each technique are discussed. Also, general evaluations of the advantages and the limitations of cooling an FTS are given.

ACKNOWLEDGEMENTS

The financial support and technical support of the Defense Nuclear Agency were instrumental in the development of the interferometer-spectrometers discussed herein. Their support is sincerely appreciated.

INTRODUCTION

Cryogenically cooled Fourier transform spectrometers are valuable tools for performing spectral measurements of weak or low temperature infrared emitting sources. In recent years, cooled FTS systems have been developed for laboratory measurements and for atmospheric and planetary studies. They have been developed for use on rockets, balloons, aircraft, satellites, and the ground.

The high sensitivities which are characteristic of these cooled spectrometers make it possible to perform studies which would otherwise be impossible or impractical. Some typical and potential uses of the instruments include the following: (1) Measurements of upper atmospheric chemiluminescence from airglow and aurora; (2) measurements of emissions generated in laboratory simulations of the atmosphere and other weak sources; (3) background studies of the atmosphere in window regions; and (4) measurements of the atmosphere and surface of planets, etc.

In this paper, some of the advantages and limitations of cooling an FTS are reviewed. Some practical cooling techniques are discussed and some descriptions of coolable Michelson interferometer-spectrometers that have been developed or used by Utah State University and the Air Force Geophysics Laboratory are presented. Also, a minimal amount of atmospheric measurement data will be presented to illustrate actual sensitivities obtained with the developed instruments.

ADVANTAGES AND LIMITATIONS

Three major advantages of cooling the optics, the detector, and the associated mounting structures of an infrared FTS are: (1) Improved sensitivity of the detector resulting in improved sensitivity of the spectrometer; (2) elimination or reduction of unwanted background signals from instrument self-emissions;

and (3) stabilized optical alignment characteristics due to temperature stabilization. Each of these advantages is briefly evaluated herein and some associated limitations or considerations are given.

Sensitivity Considerations

The noise equivalent spectral radiance (NESR) of an FTS which characterizes its sensitivity can be expressed as

$$NESR = \frac{NEP}{A\ \Omega\ \Delta\sigma\ \eta_s\ t^{\frac{1}{2}}}\ w/cm^2 sr\ cm^{-1}, \qquad (1)$$

where A is the collecting area, Ω is the solid angle field of view, $\Delta\sigma$ is the spectral resolution in cm^{-1}, η_s is the total efficiency of the spectrometer, and t is the measurement time in seconds. An equivalent expression for a standard Michelson interferometer-spectrometer is

$$NESR = \frac{4\ f/\#}{D^* \pi\ \Delta\sigma\ D_o\ \eta_s\ (\pi\ \lambda_s\ \Delta\sigma\ t)^{\frac{1}{2}}} \qquad (2)$$

where D_o is the diameter of the optics, λ_s is the shortest wavelength of interest in centimeters, f/# is the focal length divided by the diameter of the detector collecting optics, and D^* is the detectivity figure of merit of the infrared detector in cm $(Hz)^{\frac{1}{2}}$/watt. From Equations (1) and (2), it is apparent that the NESR of the spectrometer is proportional to the NEP of the detector or inversely proportional to the D^* of the detector. Thus, as expected, the sensitivity of a spectrometer can be improved by increasing the D^* of its detector.

The D^* of most state-of-the-art photon detectors can be significantly increased by cooling the background around them. To understand the magnitude of this improvement, it is worthwhile to consider the characteristics of an idealistic photon detector which is free from noise except for the noise generated by the random arrival of photons. As explained by *Hudson* [1969] and *Huppi* [1977], the theoretical D^* of an ideal photon detector is given by

$$D^*_\lambda = \frac{C_1 \lambda}{2hc} \left(\frac{\eta}{Q_b}\right)^{\frac{1}{2}} \quad \frac{cm(Hz)^{\frac{1}{2}}}{W} \qquad (3)$$

where C_1 is a constant equal to $\sqrt{2}$ for photovoltaic detectors and 1 for photoconductive detectors, λ is the wavelength in micrometers, h is Planck's constant (6.625×10^{-34} W sec^2), c is the velocity of light (3×10^{14} μm/sec), η is the detector's quantum efficiency ranging from 0 to 1, and Q_b is the total photon flux density falling on the detector (photons/cm^2 sec). Thus, for the idealized detector, the D^* is limited by the flux density (Q_b) of the background seen by the detector. If the detector views a blackbody background of known temperature, then Q_b as a function of detector cutoff wavelength, λ_c, and temperature, T, is given by

$$Q_b(\lambda_c, T) = \int_0^{\lambda_c} \frac{2\ \pi c \times 10^8}{\lambda^4 \ \exp\ (Hc/\lambda kT)-1}\ d\lambda . \qquad (4)$$

Using this equation, the plot shown in Figure 1 was generated to illustrate reductions in Q_b which are obtainable under reduced temperature conditions. For example, when a blackbody background seen by a detector with a 5 μm cutoff wavelength is cooled from 300°K to 80°K, the radiant photon emittance is reduced from 10^{16} to 10^4 photons/sec cm^2. Theoretically, Equation (3) would predict this to increase the D^* of the detector by $(10^{12})^{\frac{1}{2}}$ or 10^6, and from Equation (2) it is apparent that the NESR of a spectrometer would be reduced by 10^6; or in other words, the instrument would be 10^6 times as sensitive.

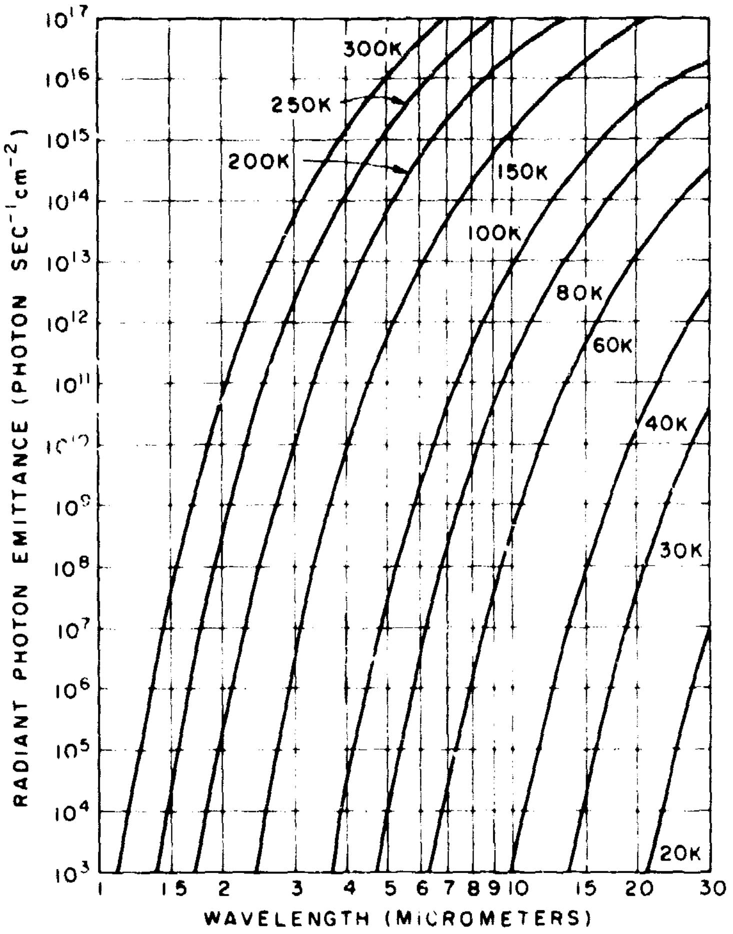

Figure 1. Blackgody radiant photon emittance versus cutoff wavelength for various temperatures.

In practice, the D^* of a detector is limited to a value less than the theoretical maximum described by Equation (3). As the noise due to background photons is reduced, other sources of noise become significant and dominant. Once these other noises dominate, no increase in sensitivity is obtained with further cooling of the background. To gain an understanding of this effect, consider the total noise current of a detector and preamplifier which is

$$i_n = (i^2_{background\ noise} + i^2_{source\ noise} + i_o^2)^{1/2} \qquad (5)$$

or, equivalently

$$i_n = (\eta\ N_b\ 2\ BW\ e^2 + \eta\ N_s\ 2\ BW\ e^2 + i_o^2)^{1/2} \qquad (6)$$

where N_b and N_s are the number of photons per second striking the detector from the background and source respectively, BW is the electric bandwidth, e is the charge of an electron, η is the quantum efficiency of the detector and i_o is a noise current generated from all sources of excess noise such as Johnson noise, 1/f noise, preamplifier noise, etc. As an infrared FTS is cooled, the background noise terms of Equations (5) and (6) become insignificant and one or both of the other two noise sources will dominate. If the source is sufficiently weak, then the noise is likely to be dominated by the excess noise terms, and the detectors, signal-to-noise ratio is directly proportional to the number of source photons. The ratio can be expressed as

$$S/N = \frac{i_s}{i_n} = \frac{\eta\ N_s\ e}{i_o} \qquad (7)$$

where i_s is the signal current generated from the source photons. Under these conditions, the noise is independent of the signal, and the noise is set by the internal characteristics of the detector and preamplifier components. The "multiplex advantage" of an FTS interferometer is typically a useful characteristic under these conditions provided proper electrical processing and filtering is used. If the source is sufficiently intense, the noise is dominated by the random arrival of source photons and the signal-to-noise ratio is given by

$$S/N = \frac{i_s}{i_n} = \frac{(\eta N_s)^{\frac{1}{2}}}{(2\ BW)^{\frac{1}{2}}} . \tag{8}$$

The signal-to-noise ratio is no longer directly proportional to the source photons. It is only proportional to the square root of the source photons. Under these source noise limited conditions, a Michelson FTS can very easily lose the effectiveness of its multiplex advantage since the noise at each wavelength is dependent on the total photons falling on the detector from all source emissions within the entire free spectral range of the interferometer. For example, the "multiplex advantage" definitely becomes a disadvantage for measurements of weak spectral features if there are other strong emitters in the free spectral range of the instrument which dominate the noise. For some of these types of measurements, a large throughput, cryogenically cooled, sequential scanning spectrometer can often be used more effectively than an FT interferometer-spectrometer.

Additional detector-related complications often occur in cryogenically cooled FT-IR interferometer-spectrometer applications. Many detectors operating in cold background conditions develop nonlinear and other undesirable characteristics which must be considered. It is often necessary to accept lower sensitivities to avoid these characteristics. A typical example of a nonlinearity, which occurs in many doped, extrinsic silicon detectors (Si:XX), is illustrated in Figure 2.

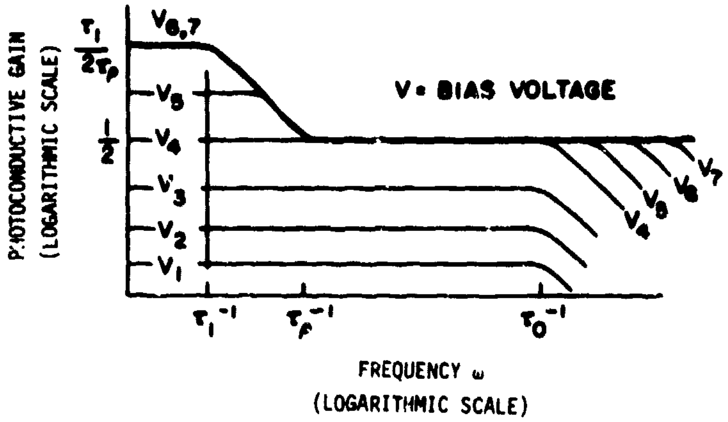

Figure 2. Theoretical photoconductive gain characteristics of an Si:As detector as a function of bias voltage and frequency.

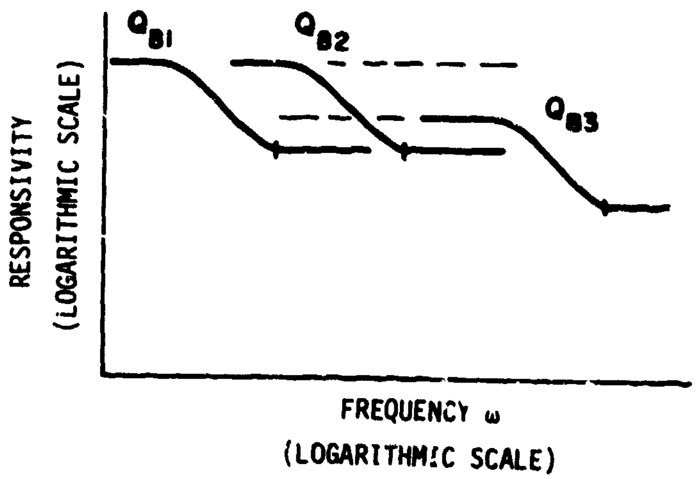

Figure 3. Detector responsivity as a function of frequency for different input photon flux levels.

As shown, the photoconductive gain of the detector is characterized by a single short time constant, τ_o, if the bias voltage is below V_4. However, if the bias voltage is increased above V_4, the photoconductive gain is enhanced at frequencies below τ_p^{-1}, and the photoconductive gain is characterized by two time constants, τ_o and τ_p. *Williams* [1969] points out that this low frequency enhancement originates from space-charge relaxation which is commonly referred to as dielectric relaxation. In addition to being bias dependent, the time constant which characterized the dielectric-relaxation enhancement is dependent on the incident photon flux level. As shown in Figure 3, the photoconductive gain response varies instantaneously with flux changes. Increasing the photon flux from Q_{B1} to Q_{B2} increases the frequency where the enhancement occurs. If an FT interferometer-spectrometer is designed to operate at frequencies around this dielectric enhancement region, several potential problems could occur. First, since the frequency response of the detector varies instantaneously with input flux, the instrument becomes almost impossible to calibrate. Secondly, if harmonic distortions are generated from this instantaneously changing response during a source measurement, erroneous spectral features will occur in the measured spectra. As indicated in Figure 2, the problem can be avoided by reducing the bias voltage below V_4. However, in actual practice the photo-conductive gain must be decreased to about .3 instead of the theoretical value of .5 shown in Figure 2. In addition to eliminating the nonlinearity problems, this bias reduction also reduces or eliminates noise from "spiking" which is another undesirable characteristic of the detector that occurs under low background conditions. The negative aspect of the bias reduction is the corresponding limitation placed on the sensitivity which forces the operation of an FTS to be lower than would commonly be predicted.

Background Reduction

Cooling an FT-IR interferometer-spectrometer reduces unwanted background signals from instrument self-emissions. If the instrument is cooled to a low enough temperature, the self-emissions can be made negligible relative to the noise level of the instrument. Under these conditions, measurements can be made and the calibration of the instrument can be performed easily and reliably, since there is no background signal from the instrument that needs to be subtracted from the measured signal. Typically, this background reduction also reduces the dynamic range requirements of the signal processing equipment. On the other hand, calibrations and measurements made with an uncooled or partially cooled instrument can be complicated if the signals are weak enough to require continuous subtraction of the instrumental self-emissions.

The magnitude of the self-emission background problem can be understood by considering the spectral emission characteristics of a blackbody at various temperatures as shown in Figure 4. The blackbody curves can be used as guidelines since they give the maximum possible background from self-emissions of the instrument. Actual instrument emissions are typically lower than these blackbody emissions because their effective emissivity is considerably less than the emissivity of a blackbody. As shown in Figure 4, it would be difficult to measure a source having a radiance of less than 10^{-9} W/cm^2 sr μm at any wavelength between 5 and 31 μm with an instrument operating at 300°K since the blackbody emissions are more than 5 orders of magnitude larger than the source emissions. Thus, even if the effective emissivity of the instrument is .01 the unwanted background spectral emissions would be more than 3 orders of magnitude above the signal. However, if the instrument is cooled to approximately 10°K, which is easily accomplished with liquid helium, the unwanted self-emissions of the instrument become insignificant relative to the 10^{-9} W/cm^{2}sr μm signal.

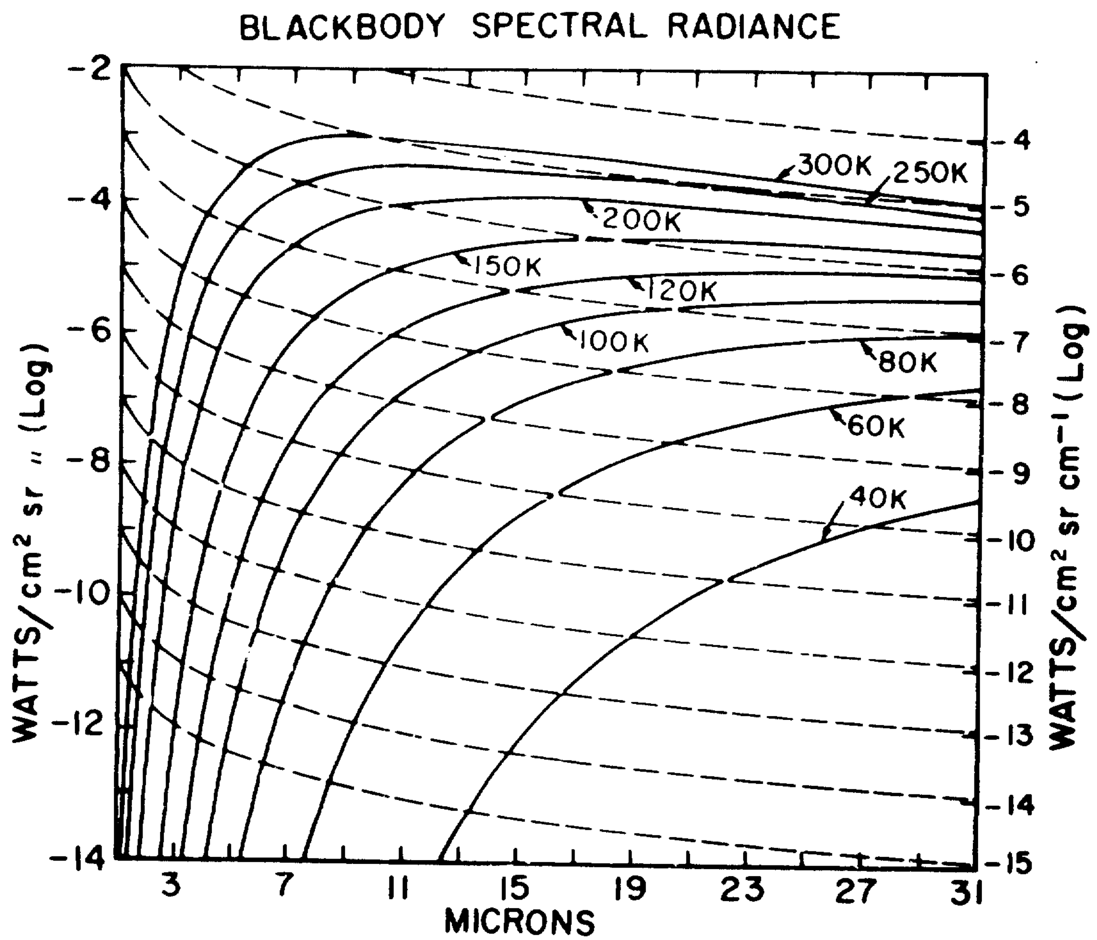

Figure 4. Blackbody spectral radiance versus wavelength for various temperatures. The dashed lines are contours of constants spectral radiance corresponding to the vertical scale on the right.

There are several techniques that have been developed to reduce, eliminate, or remove the unwanted self-emission backgrounds from the source signal of a spectrometer without cooling it. For example, the instrument background can be substantially reduced by employing low emissivity mirrors, anti-reflection coated optics, optical systems which image cold detectors back upon themselves, and spectral band-limiting cold filters. The unwanted background can be further removed through the use of cold reference sources as summarized by *Huppi* [1977]. However, these cold reference subtraction techniques are not always simple to perform and they often give less than satisfactory results. Thus, considering the cryogenic technology which has been recently developed and successfully used by USU, AFGL and others, it is probably as simple and it is definitely better to reduce the background self-emissions of an infrared, interferometer-spectrometer by cooling the entire instrument.

Optical Alignment Stabilization

Cryogenically cooling an FT-IR interferometer-spectrometer with a properly designed dewar and mounting system stabilizes its operating temperature. The stabilized temperature eliminates unwanted movements of the optical components due to thermal expansions and contractions. As a result, the optical components which form the interferometer stay in very good alignment while the instrument remains cold, and a very stable response is produced.

Tests on a Michelson interferometer-spectrometer similar in design to the one used in DNA's EXCEDE program [*Kemp and Huppi*, 1980] indicate that the response of a spectrometer can remain constant within ±1% over several days if it is kept continuously cold. Thus, the periodic need to calibrate an interferometer throughout a measurement sequence can be avoided. This can be of significant importance when it is desirable to make very accurate comparisons between spectra taken in a measurement sequence which extends over a period of time.

Cooling an interferometer-spectrometer strictly to gain alignment stability is probably not justifiable in most cases, but it is a nice improvement which adds to the advantages of cryogenically cooled FTS systems.

INSTRUMENTATION DESCRIPTIONS AND MEASUREMENT EXAMPLES

A number of cryogenic FT-IR Michelson interferometer-spectrometers have been developed and operated by USU and AFGL. Three different types of mirror-drive mechanisms have been used in these instruments, and examples of each are presented in this section.

Interferometer Incorporating Flex Pivot Drive System

A pictorial view of a very compact Michelson interferometer modulator cube and drive mechanism is shown in Figure 5. The unit has been cryogenically cooled, and *Kemp and Huppi* [1980] have reported on its use in a rocket-borne application. It has also been used in a reduced temperature balloon-borne application by *Huppi et al.* [1979]. The interferometer design is patterned after one which was initially developed by John Rex of AFGL. A parallelogram arrangement with pivots at the corners is used to translate a movable end mirror in a standard Michelson modulator arrangement. Figure 6 is a detailed drawing of the drive mechanism. The pivot points and three sides of the parallelogram structure are shown. The fourth side is formed by a portion of the cube structure which locates and fastens the two upper sets of pivots. Friction-free flex pivots made by Bendix, Inc., are used to allow rotation at the pivot points. A torque motor is used to change the angles formed at the corners of the parallelogram. Almost constant mirror velocity is maintained by using velocity and position feedback obtained from a tachometer and differential transformer. Parallel translation

Figure 5a. Cryogenically coolable interferometer cube and drive mechanism.

Figure 5b. Optics and drive parts of the interferometer.

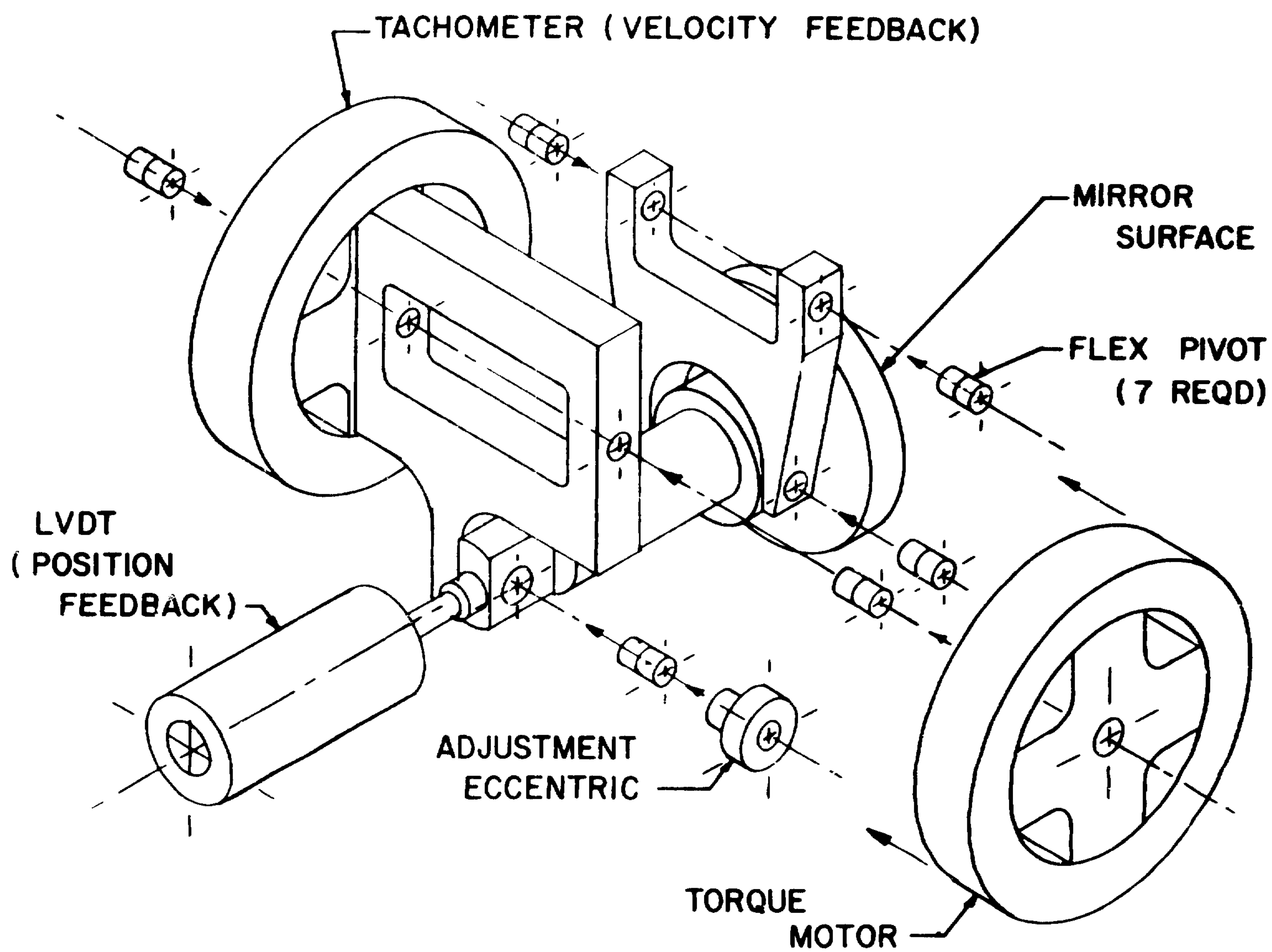

Figure 6. Detailed pictorial drawing of flex-pivot interferometer drive mechanism.

of the mirror surface results as long as the opposite sides of the parallelogram are kept equal in length. The lengths remain equal if they are made from the same type of aluminum and if they are uniformly cooled. Typically, the mirror surface varies less than 1 arc sec over a .55 cm translation distance which is obtainable with the small cube and drive assembly. The overall physical size is approximately 4 in.x 4 in. x 7 in.

Either conductive or convective cooling techniques can be used to cool the interferometer. A dewar arrangement that has been developed for rocket-borne use and provides convective cooling is shown diagrammatically in Figure 7 and pictorially in Figure 8. As shown, the interferometer is conductively bolted to a cold finger and placed in a sealed chamber which has been evacuated and back-filled to one third of an atmosphere with N_2 gas. This chamber and the cryogen chamber are thermally isolated from the outer shell by a vacuum envelope and many layers of super insulation. Very uniform cooling of the interferometer parts is accomplished through the use of this technique, and excellent performance has been obtained. However, the sealed chamber and the sealed window which are used in the technique complicate the dewar design and limit the useable spectral range to the transmission region of the window. Therefore, a conductive cooling approach is sometimes more desirable. The flex-pivot interferometer can be cooled conductively by adding copper straps to the rear portion of the parallelogram drive mechanism as shown in Figure 9. The main structure of the cube must then be bolted to a cold finger in a dewar as before.

Both cooling techniques provide an excellent mechanism for achieving improved sensitivity, reduced background self-radiation emissions, and stable optical alignment characteristics. NESR's in the range of 10^{-11} W/cm^2 sr cm^{-1} have been obtained in a 1.6 second time interval at 2 cm^{-1} spectral resolution with a flex-pivot instrument operating at 77^{o}K incorporating an InSb detector.

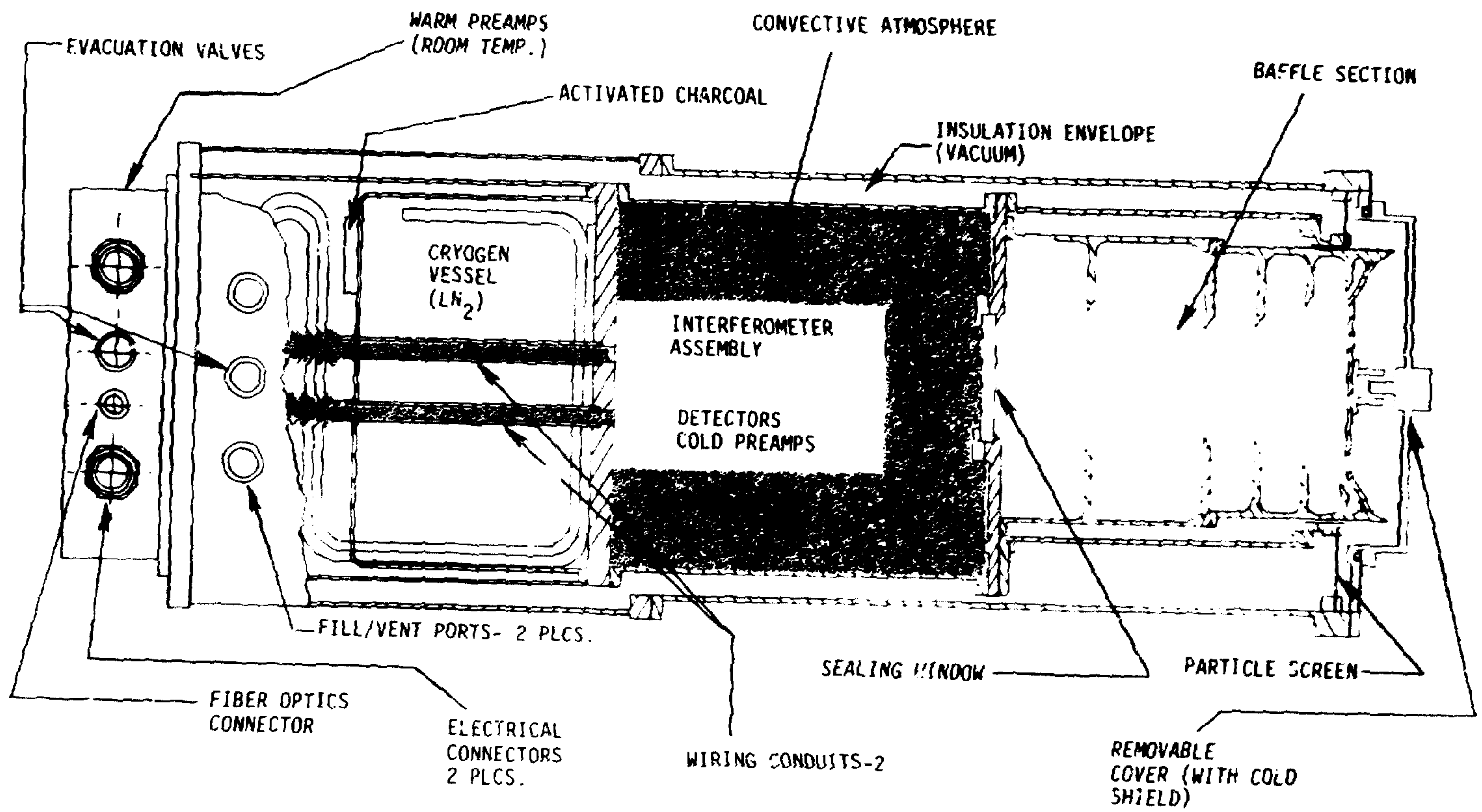

Figure 7. Schematic of cryogenic interferometer dewar with convective cooling chamber.

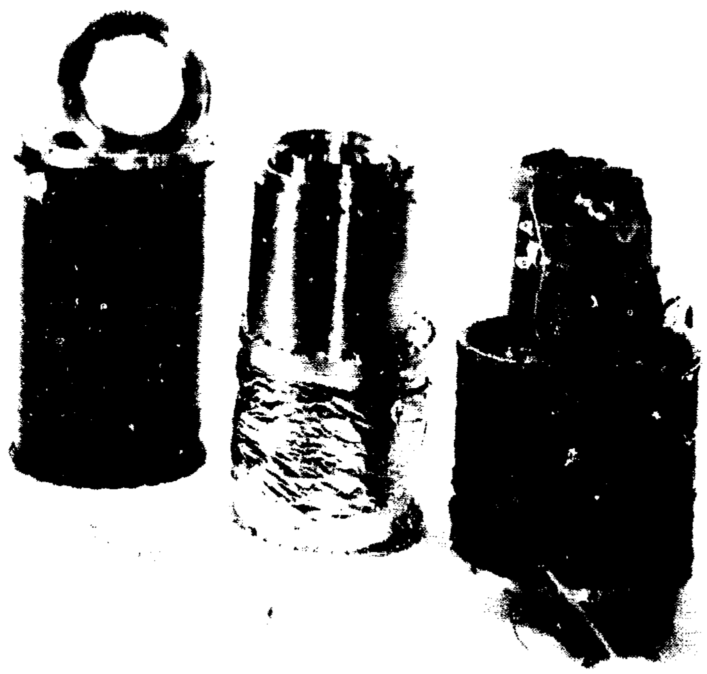

Figure 8. Pictorial view of interferometer dewar with convective cooling chamber.

Figure 9. Flex-pivot interferometer with conductive cooling straps.

Interferometer Incorporating Ball Bearing Slide Mechanism

Another Michelson interferometer system which has been successfully used in a rocket-borne upper atmospheric measurement application is shown in Figure 10. The instrument was developed for AFGL cooperatively by Idealab and Honeywell Radiation Center, and its characteristics have been reported by *Bohne, et al.* [1975]. The instrument is cooled by conduction to approximately $10^{o}K$ with a super critical liquid helium system. The interferometer base is mounted to the helium storage chamber at only one point in the right-hand portion of the dewar as shown in Figure 10. The various parts of the instrument are cooled and thermally stabilized with conductive copper straps. The slide mechanism consists of a ball bearing and V groove arrangement made from A-2 steel as is the entire interferometer structure. One mirror surface of the standard plane mirror Michelson interferometer arrangement can be translated a maximum distance of 1.1 cm, and the total angular variation of its surface is about 5 arc seconds throughout the translation. The instrument uses an Si:As detector to cover the 4 to 20 μm spectral range. NESR's in the range of 1×10^{-11} W/cm^2 sr cm^{-1} have been obtained at 2 cm^{-1} resolutions in a 0.5 second measurement time.

Field-Widened Interferometer Incorporating Gas-Lubricated Slide System

A group of very sensitive cryogenically cooled interferometer-spectrometers having a large collecting area and a wide field of view have been developed by Utah State University. The optical design used in the instruments was first proposed by *Bouchareine and Connes* [1963] and the implementation of the design into practical, cryogenically coolable instruments has been described by *Steed* [1979]. The technique uses prisms as end mirrors to accomplish field-compensation or field-widening.

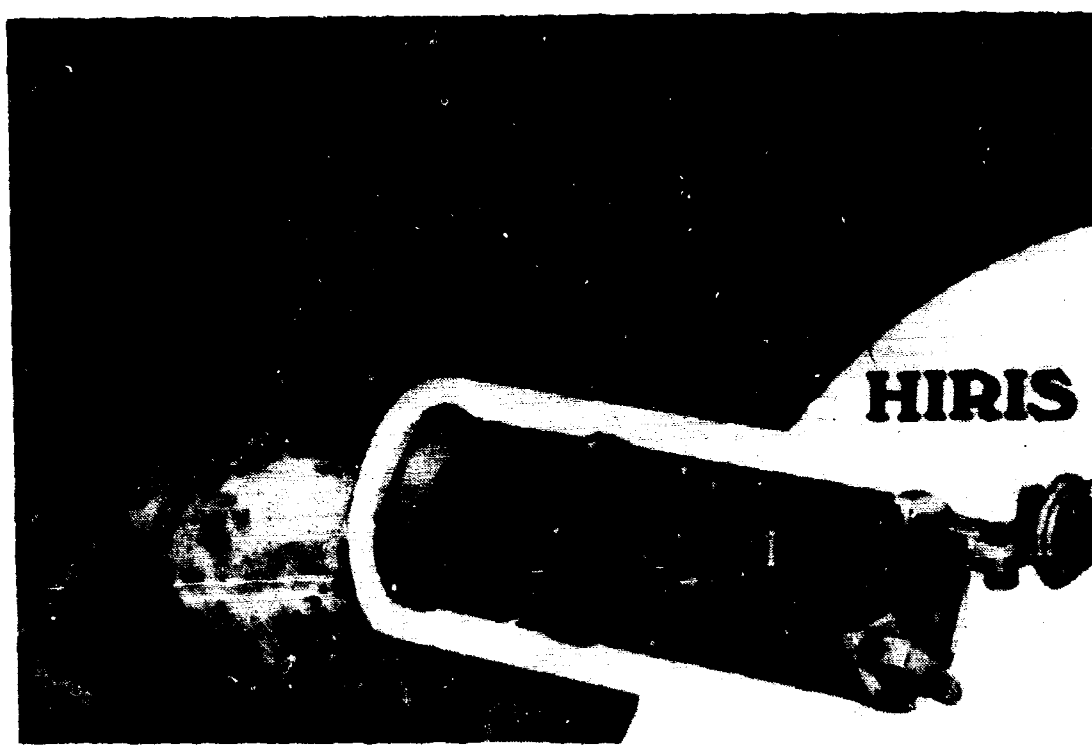

Figure 10. Conductively cooled Michelson interferometer and dewar system (courtesy of Honeywell Radiation Center, Lexington, Mass.).

The optical path difference between the two paths of the interferometer is changed by translating a wedge to vary the thickness of the optical material in one arm. An optical layout of the system is shown in Figure 11. The instrument uses an electromagnetically driven gas-lubricated slide assembly to translate the movable wedge. This slide assembly is the most critical mechanical component in the interferometer since very precise translation of the wedge and mirror is needed. A drawing of the slide assembly is shown in Figure 12, the pictorial views of actual slides developed for ground operation and rocket-borne use are shown in Figure 13. The movable portion of the slide has a trapezoidal cross section and fits precisely between three gas-lubricated bearing surfaces. The slide can move a total distance of 5 cm and maintain less than 0.1 arc seconds of tilt. Cold gaseous N_2 or He is used for the bearing lubricant. The gas lubricant is obtained from a liquid reservoir which is heated to produce the cold gas. The cold gas supplied to the bearing also convectively cools the instrument, since it flows into a chamber containing the instrument after it escapes from the bearing. As the pressure builds up in the cold chamber, the cold gas is released around an optical viewing window in the chamber. If N_2 gas is used, the window is kept frost free by the cold N_2 gas which escapes around the window. This is accomplished by placing a baffle around the window so that the cold gas, which is heavier than the ambient air, will collect on top of the window and prevent the moist air from making contact with it. A pictorial view of a ground-based field-widened interferometer system which incorporates these cooling techniques is shown in Figure 14.

A sample of some data collected with the ground-based interferometer-spectrometer is shown in Figure 15. It consists of a night sky emission spectrum of upper atmospheric hydroxyl emissions. The instrument incorporated a liquid nitrogen cooled optical system and a liquid helium cooled bismuth doped silicon detector to obtain a very high sensitivity. As shown in the data, the noise level of the instrument is extremely small.

CRYOGENICALLY COOLED FIELD-WIDENED INTERFEROMETER

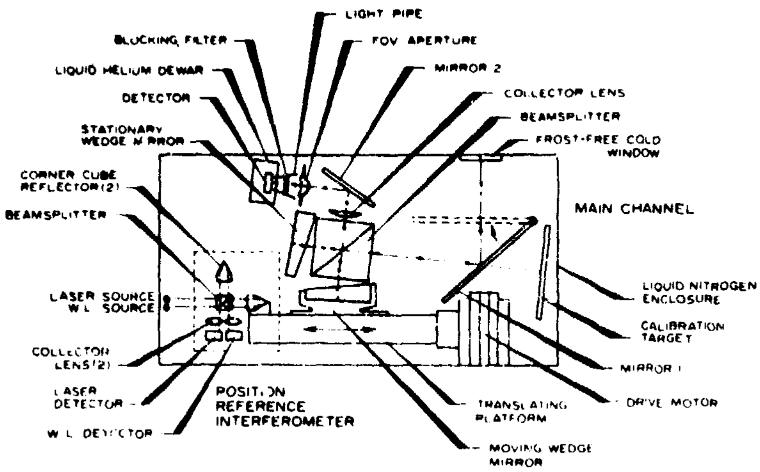

Figure 11. Cryogenically cooled field-widened interferometer.

GAS-LUBRICATED SLIDE ASSEMBLY

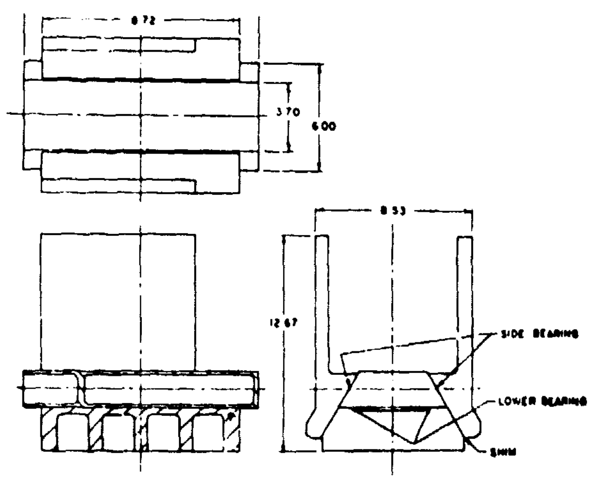

Figure 12. Gas-lubricated slide assembly.

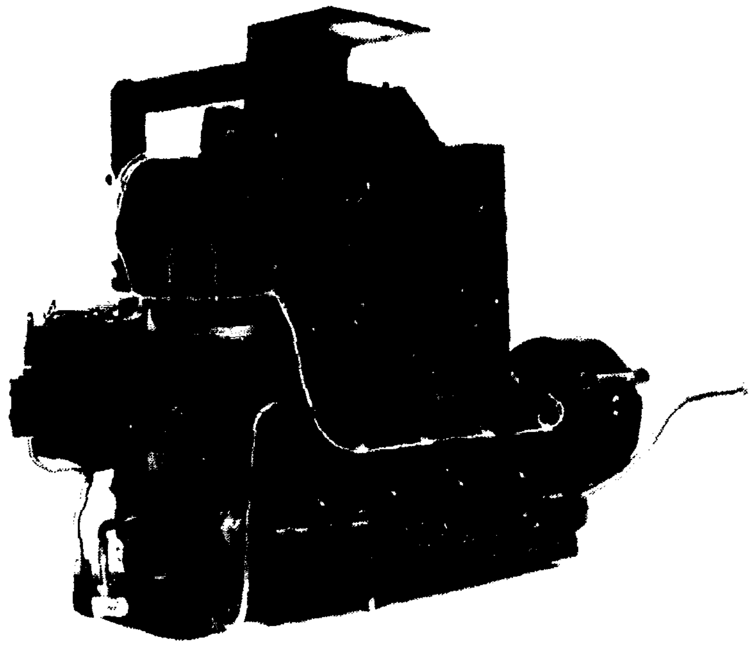

Figure 13a. Cryogenically coolable gas-lubricated slide developed for ground-based use.

Figure 13b. Cryogenically coolable gas-lubricated slide developed for rocket-borne use.

Figure 14. Ground-based field-widened interferometer system.

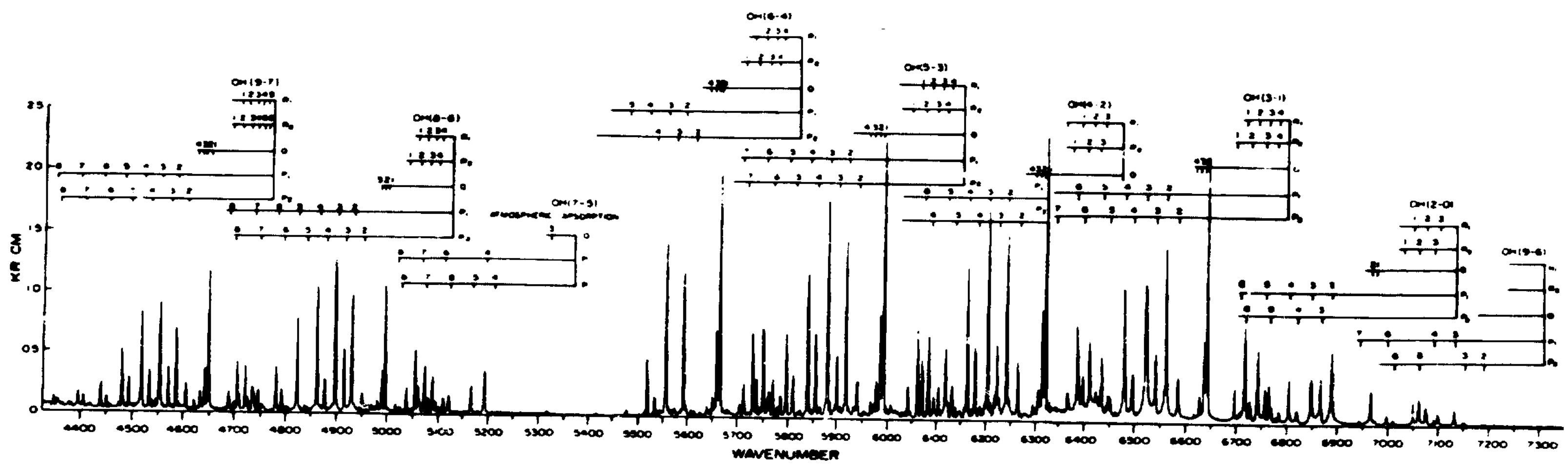

Figure 15. Night sky hydroxyl emission spectra with 2.5 cm^{-1} spectral resolution measured at White Sands, New Mexico, on December 3, 1975, over a 10-minute time interval.

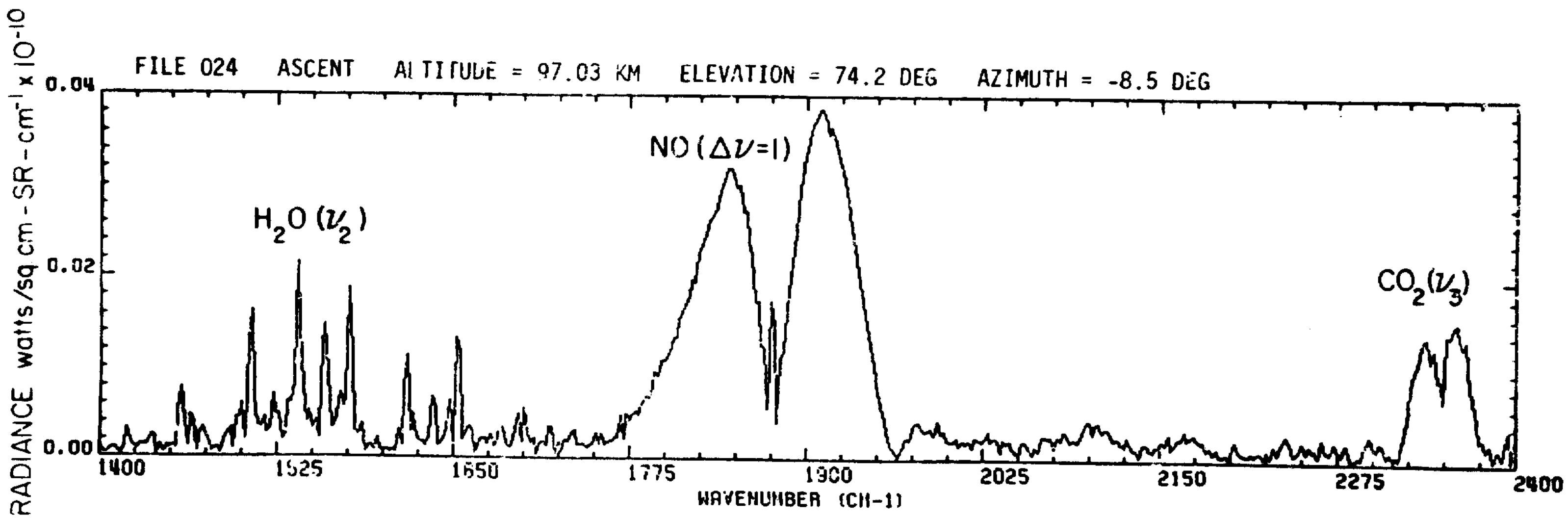

Figure 16. Upper atmospheric night sky emission spectrum measured with a rocket-borne, cryogenically cooled, field-widened interferometer.

and excellent signal-to-noise measurements were obtained of the weak hydroxyl emissions over the 10-minute measurement time.

Figure 16 shows an example of some data taken with a cryogenically cooled rocket-borne field-widened interferometer viewing the night sky at 74.2 degrees elevation from an altitude of 97.03 km. The spectrum consists of very weak nitric oxide and carbon dioxide emitters which apparently are still present at the measurement altitude. The H_2O emissions in the spectrum probably come from small amounts of water which were outgased from the payload. The NESR of the cryogenically cooled interferometer-spectrometer which measured the spectrum was less than 2×10^{-13} W/cm^2 sr cm^{-1} at 5 μm for a 1.5 second measurement time and a spectral resolution of 2 cm^{-1}. The optics and instrument structures were cooled with liquid N_2, and the extrinsic silicon detector was cooled with liquid He. The excellent sensitivity obtained with the spectrometer is orders of magnitude better than any known uncooled spectrometer that has been developed for the same spectral region, and thus, the major advantage of cryogenic cooling is very apparent.

CONCLUSIONS

Cooling an FT-IR interferometer-spectrometer can substantially improve its sensitivity, reduce or eliminate its unwanted background signals from self-emissions, and stabilize its optical alignment. The improvements in performance increase the capability of a spectrometer to spectrally measure weak infrared sources which otherwise could not be measured. Although the advantages of cryogenic cooling can be significant, several undesirable characteristics can occur which limit the improvements. Since some of these limitations are source dependent, it is necessary to understand the limiting characteristics before attempting to develop a cryogenically cooled spectrometer for a specific application.

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